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REPORT No. 31/R/48

20071109140

THE ASSESSMENT OF LIQUID PROPELLANT INJECTORS

Part II. The Measurement of Droplet size distribution by
Direct Photography with "Microflash" Illumination

G. K. Adams

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R + D Abstracts Vol 10, 1957
DATED 1957 BY *246*

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PART II. The Measurement of Droplet size Distribution by
Direct Photography with "Microflash" Illumination

By

G.K.Adams

This report does not contain material of overseas origin

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C.S., E.R.D.E.

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SUMMARY

1. Object of Investigation

To explore the usefulness of direct photography in the measurement of droplet size distribution in sprays from liquid propellant injectors.

2. Scope of Investigation

An apparatus for the low power photomicrography of sprays with spark illumination has been set up, and a technique developed for the measurement and counting of the droplet images. The optimum conditions and possible accuracy of the measurement of the distribution of droplet sizes within the spray have been investigated. The results obtained with several types of injector are given in illustration of the method.

3. Conclusions

The use of direct photography for the assessment of injector sprays has great advantages in flexibility of application to varying types of injector and conditions of operation. It is the only method which can give information on the incipient state of atomisation close to the orifice and under conditions other than those in the free atmosphere. The instantaneous character and the limited volume of the sampling are disadvantages when time average distributions over a large spray volume are required. A measuring and counting technique is described which reduces to a minimum the time and labour consumed in measuring up a large number of photographs.

Measurements on a system having a known particle size distribution have shown fair reproducibility with counts of only 500 particles. There appears to be a systematic error in the measured distribution curve due to the small depth of field. The volume median diameter is underestimated by about 10% for a distribution centred around 200μ and a small amount of distortion is introduced into the distribution curve. This degree of accuracy should be sufficient for the applications of droplet size distribution data envisaged, which are comparative rather than absolute.

References

1. The Assessment of Liquid Propellant Injectors. Part I. Atomisation; its measurement and influence on combustion efficiency of rocket motor. E.R.D.E. Technical Report 28/R/48.

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LIST OF FIGURES

1. Photograph of light source, spray chamber and camera.
2. Schematic diagram of the above and pressurised liquid supply.
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5. Distribution curves obtained from these negatives.
6. Distribution curves obtained for paraffin wax suspension.
7. Spray pattern given by dithekite injector with slotted plug.
8. Dithekite injector - flow calibration.
9. Dithekite injector spray close to orifice (with helical plug).
10. Ditto using slotted plug.
11. Distribution curves and spray pattern of inner orifice of HNO_3 /Kerosene injector No.4087.

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Introduction

The principles of the photographic method have been discussed in the first part of this report.

The aim is to obtain a certain degree of definition over the maximum depth of field. The optimum condition occurs when the diameter of the circle of confusion (referred to the object plane) which is directly proportional to the numerical aperture of the lens system, is of similar order to the limit of resolution due to diffraction by this aperture. This is inversely proportional to the numerical aperture and the optimum depth of field can be shown to be proportional to the square of the resolution required and independent of the degree of magnification. At a fixed value of the numerical aperture, the depth of field depends linearly upon the diameter of the circle of confusion; thus, for large drops, where poorer definition can be tolerated, the apparent depth of field increases. Experiment has shown that for droplet distribution with volume median diameters of 200μ the volume of spray sampled is approximately 7 by 5 by 1 cm. at each exposure.

Since the droplet distribution is examined within a volume element small compared to the extent of the spray, and since the state of atomisation increases with increasing distance from the injector orifice, it has been found convenient to measure the mean distribution over a cross section of the spray at a constant distance from the orifice. The distance at which a stable droplet system is reached varies with type of injector and the conditions of operation. The position and number of the sampling volumes chosen will be determined by the type of spray examined. The samples are given their appropriate weight and averaged over the total cross section.

Experimental Method

The arrangement of the camera, light source and spray is shown in fig. (2). The camera is of the fixed focus type and uses a 36 cm. focal length Skopar lens covering the relatively small image area of 9 x 12 cm. Standard metal dark slides with cut film adaptors are used and a ground glass screen is provided for focussing the camera on the desired area. The use of a long focal length camera lens is dictated by the necessity of a convenient working distance between the spray and the lens, 50 cms in the present instance. In the preliminary experiment various magnifications were tried; the maximum magnification is limited by the light output of the source of illumination and the sensitivity of the emulsion; the minimum value is fixed by the resolution of the emulsion. This latter for process films, is about 10μ giving a minimum magnification of one half which would entail the use of a high degree of enlargement in the subsequent projection of the image. A magnification of 1.8 was found to be most convenient.

The minimum numerical aperture for a given resolution can be obtained from equation (16) P.26; ref.1, this is related to the f. no. of the lens and the magnification M, by the following equation; by the usual convention M is taken to be of negative sign.

$$N.A. = \frac{1}{2(f.no.)} \frac{M}{M-1} \quad (1)$$

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For a resolution of 20μ the minimum numerical aperture for light of wave length 0.45μ is 10^{-2} ; thus the required f. no. with a magnification of 1.8 is f 1.32.

At this aperture and with the narrow field used, the residual aberrations of the objective, with the exception of chromatic effects are negligible. The latter are minimised by using a source rich in the blue-violet-range of the spectrum and a non-colour sensitive emulsion. The Mullard L.S.D.2. tube used is said to have its maximum output at 0.42μ and process emulsions have a maximum sensitivity at 0.45μ . It was found desirable to use a slow emulsion in order to obtain a high degree of contrast; Ilford process film developed in I.D.2. developer at 18°C for five minutes was found suitable.

The light source is a Mullard L.S.D.2 flash tube, discharging a 2 mfd. condenser charged to 7.5 KV; the power supply and triggering circuit are conventional. The tube is placed at the centre of curvature of a reflector and is imaged on the diaphragm of the objective by means of the condenser lens L_1 of 50 cms. focal length. The field illuminated is restricted to that covered by the camera means of the diaphragm D_1 . The effective photographic duration of the flash of the L.S.D.2. tube under the above operating conditions was found to be two to four micro-seconds, somewhat longer than that quoted by the makers. It is, however, short enough to give sharp images of droplets moving with a speed of less than five metres per second. The results suggest that this condition holds for most sprays, at distances of about 15 cms from the orifice, with injection pressures of up to twenty atmospheres.

To obtain a good definition of the nascent spray at points close to the orifice, where the velocity is not much less than the theoretical value (if $\Delta p/p = 10$ atms/gms/cc, $v = 44.5$ metres/sec.) it would be desirable to use flashes of not greater than 0.5μ s duration. The duration of the discharge is roughly proportional to the capacity of the discharge condenser; and the energy of the flash, to the product of the capacity and the square of the voltage. Thus, in order to maintain the same light output while reducing the capacity by one quarter, it is necessary to double the voltage. The L.S.D.2. tube becomes unstable at voltages over 12 KV so that it is not possible to modify the standard type of equipment to give shorter flashes at the same light output. It is intended to use a triggered magnesium gap in air with voltages up to 20 KV to give a series of half-micro second flashes at 100-1000 μ s intervals. This could be used in conjunction with a rotating mirror camera to give consecutive photographs of the behaviour of jets close to the orifice and at points of impingement and of the behaviour of injectors for self igniting fuels during starting conditions.

As can be seen from the diagram, the injector sprays into a metal tank with windows on each side placed between the condensing lens and the camera. The tank has an outlet at its base, so that the sprayed liquid may be drawn off, and has at the top an adjustable clamp for the injector. This is constructed so that the position of the injector can easily be altered by movement along the optical axis and in the vertical and horizontal directions perpendicular to it. It can be tilted in the vertical plane containing the optical axis, so that the direction of motion of the drops can be made parallel to the object plane, and can be rotated about the injector axis. By this means the position of the injector can be varied so as to bring the parts of the spray selected for sampling into the field of the camera and illuminating system. The decision as to the number and position of the photographs made with each spray depends on the type of spray injector, i.e. centrifugal or

/impinging

impinging jet, the degree of symmetry of the spray and the distribution of density. The latter is best determined by making a preliminary patterning test. Two methods have been used: in the first the distribution is examined qualitatively by spraying on to a liquid surface as in fig. (7); in the second, the spray is directed for a convenient time into a tray divided into sections, the volume collected in each section, measured and the fraction of the total volume calculated. The type of tray used for centrifugal sprays is shown in fig. (11).

At the moment of writing only one pressurised supply of liquid is available; the liquid is held in a spherical aluminium container of 60 litres capacity which can be pressurised up to forty atmospheres with compressed air or nitrogen. The liquid is fed via a valve and flexible hose to the injector, a head measuring gauge being inserted into the supply line just before the injector. A gauze filter is inserted between the supply tank and the measuring point to prevent particles of scale from the piping system blocking the injector orifices. The layout of this supply is shown in fig. (2).

Two other sources of the supply are in process of installation; a high pressure (up to 100 atmospheres) reciprocating water compressor and a pump for kerosine. In the meantime the single pressure vessel is used both for kerosine and for water. The injectors which have been examined are designed for use with the nitric acid/kerosine bipropellant and the monopropellant dithekite. Up to the present it has not been practicable to use nitric acid or dithekite in spray tests. The relevant physical constants of 98% nitric acid and dithekite are as follows at 25 C:-

Propellant	Density g/cc	Kinematic viscosity cs.	Surface tension dynes
Dithekite D.13	1.37	1.18	41.5
98% nitric acid	1.51	0.60	40.

Liquids with physical properties similar to those of nitric acid and dithekite have not been available. Injectors designed for use with these liquids have been tested with water; it is possible that the effect of density may be allowed for by comparing the results at a constant value of $\Delta P/\rho$ but not enough is known of the effect of surface tension to allow conclusions to be drawn about the drop size distribution of one liquid from measurements with another.

The greater part of the time required for the assessment of drop size distribution in injector sprays is consumed in the evaluation of the negative. For many comparative purposes it is sufficient to make an enlarged print when major differences in the average drop size are apparent to the eye. If more exact information is required, the images must be measured and counted. This can be done with a low power microscope and an eye piece with a graticule, but it is far less fatiguing when counting large numbers to project the negative on a ground glass screen in a slightly darkened room. The most useful method of presentation of drop size data is in the form of a graph of the cumulative volume fraction oversize. If the curve should fit the Rosin Rammler distribution law, which can be ascertained by plotting values of $\log \log 1/R$ (R is the volume fraction of spray having diameter $> d$) against values of $\log d$ when a straight line of slope n should be obtained, the distribution can be expressed in terms of a size constant d_0 , above which lies $1/e$ th of the total spray volume, and the distribution constant n according to the equation

$$R = e^{-\left(\frac{d}{d_0}\right)^n} \quad (2)$$

/The

The volume distribution curve is obtained by dividing the total range of droplet sizes into groups and counting the number of droplets in each group. This number is multiplied by the cube of the mean diameter of the group to obtain the incremental volume, and this, divided by the sum of the incremental volumes of each group, gives the volume fractions in each size group. Thus, if N_i is the number of droplets having diameters between d_i and $d_i + \delta d$, and if the arithmetic mean diameter of the group $d_i = d_i + \delta d/2$, is taken:

$$R_i = 1 - \frac{\sum_{j=0}^{i-1} N_j d_j^3}{\sum_{j=0}^{\infty} N_j d_j^3} \quad (3)$$

R_i can then be plotted against d_i to give the required distribution curve. It is found in practice that the number distribution curve has a maximum, and it is only necessary to consider droplet sizes down to about one tenth of the size of the largest droplet in the spray sample, the volume fraction of droplets below this size being negligible. It is convenient to divide the total range of diameters into about ten equal groups for the purposes of measurement and computation. Since the limit of resolution imposed by the optical systems is about 20 microns, the minimum increment of diameter which has significance is about twice this. For sprays with size constants of less than 200 microns, the error in the distribution curve due to the finite width of the diameter increments may become appreciable. In order to find the magnitude of this error the distribution curve for 40 micron diameter increments was calculated for a spray having a distribution given by the equation:-

$$R = e^{-\left(\frac{d}{200}\right)^4}$$

The method and details of the calculation are given on P.39 of ref.1.

$\frac{d}{200}$	0.1	0.3	0.5	0.7	0.9	1.1	1.3	1.5	1.7
R	.9999	.9919	.9394	.7866	.5169	.2322	.0578	.0061	.0002
R for 40 μ intervals	1.0	.9938	.9456	.7997	.5230	.2362	.0595	.0065	.0000
$\delta \times 10^4$	1	19	162	131	61	40	17	4	2

The differences are surprisingly small and are well below the experimental error. They will of course, increase rapidly with increase of $\delta d/d_c$.

In order to facilitate the measurement of the number of drop images having diameters between d_i and $d_i + \delta d$ the following technique was developed. The drop images are projected on to a ground glass screen; the magnification can be varied between five and twenty five diameters by adjusting the projection distance. The image is viewed from the side of the screen far from the projector, the ground surface being placed on this side of the glass sheet to avoid parallax errors. The drops are compared in turn with the adjustable calipers illustrated in fig. 3. This has ten settings of the distance between the measuring

/edges

edges from 2 mm to 20 mm increments. The setting is determined by the position of the ten pole selector switch by means of a wire winding on the axle of the switch. The contacts of the switch are used to select one of ten telephone message counters. The calipers are placed on the glass screen over a drop image and adjusted so that the drop diameter is less than the distance between the straight edges but greater than the distance between the next lowest setting, and the counter circuit completed by pressing the key. This registers the drop on the appropriate counter and at the same time marks the ground glass screen at the position of the drop image by means of a piece of pencil lead attached to the key. Thus drop images which have been counted can be readily differentiated from uncounted images. Prior to the count the magnification of the projection system is adjusted so that the diameter of the image of the largest drop to be counted lies within the largest setting of the calipers. Then the images down to a tenth of this largest diameter may be sized into ten groups. A counter circuit which is independent of the selection switch registers the total number of drops counted. It has been found that, in order to obtain a reproducible distribution curve, a minimum of 500 drops, excluding the lowest diameter interval must be counted. Therefore, for each sample of the spray for which a distribution curve is desired, a volume of the spray such that it contains not less than this number of drops must be assessed. If a value of the depth of field is assumed, the concentration of liquid in the spray can be calculated from the total drop volume and the volume corresponding to the negative area. Since, as has been mentioned, the depth over which the spray is measured tends to increase with drop size, it is safer to restrict comparative densities calculated in this way to sprays of similar orders of drop size.

The size distribution curve for a complete cross section of the spray can be calculated from the distribution measured at a number of sampling points by summation, each curve being weighted by the volume fraction of spray passing through the area represented by the sample, as in the example at the foot of page 8. In many instances the distribution curves for each sampling position are not required and it saves time in calculation to add the drop number/size counts together and to calculate the overall distribution from the total. It is then necessary to ensure that the sampling volume, i.e. the negative area counted is a constant fraction of the spray volume sampled. For instance if the cross section is divided into annular segments as in fig. 11 the negative area counted for section A and C would be in the ratio of the radial distances of the sampling positions. The smallest negative area taken should be large enough to make plausible the assumption that the liquid density over the sampling volume is close to the time average value.

The reproducibility and the accuracy of the computed distribution curves obtained from photographs of sprays extending over depths greater than the theoretical depth of focus were examined by taking photographs of a suspension in water of paraffin wax spheres contained in two glass absorption cells, respectively 1 cm and 2 cms. thick. The distribution curve for the wax suspension was also determined by sampling on a slide and measuring the spheres in a microscope field with a comparison eyepiece; this latter distribution curve is reproduced in curve of fig. (6). It obeys the Rosin Rammler curve

$$R = e^{-\left(\frac{d}{237}\right)^{4.9}}, \quad 0.1 < R < .99$$

/Curves

Curves B and C are the distribution curves of the suspension photographed in cells 1 cm. and 2 cms. thick respectively. They do not give a straight line from a plot of $\log \log \frac{1}{R}$ against $\log d$; therefore it is not possible to estimate the small change in the value of n , the distribution constant. The value of d_0 for $R = 1/e$ can be seen from the curves to have decreased from 237μ to 230μ and 220μ in the case of the 1 cm. and 2 cm. cells respectively. When the curves are superimposed at $d = d_0$ it is evident that above 200μ they are similar, while in the lower drop size ranges the values of R for curve C lie above those for B which in turn exceed those of curve A. This confirms the prediction that as the depth of field is increased the larger droplet sizes will be over-weighted. The apparent shifting of the curves toward the origin can be explained as being due to the under-estimation of drop diameters when the drops are at the extreme limits of the field. In the photograph of one centimeter thickness of suspension most of the images appeared to be sufficiently well defined for measurement. The practical depth of field is therefore several times greater than the theoretical*, and the explanation of this probably lies in the high contrast of the emulsion. It would have been interesting to examine the accuracy of the method using other drop size distributions but it was decided that the degree of accuracy required did not warrant an extensive investigation of the absolute accuracy of the technique. The number of samples required to give adequate representation renders the method somewhat laborious for the precise measurement of overall drop size distribution except when the total spray volume is small or the droplet distribution is spatially homogeneous.

Results

The general application of the method to rocket injectors can best be seen from the following examples. Droplet size measurements are useful only in so far as they may enable predictions to be made of their performance in the rocket motor. As has been stated in the first part of this report, knowledge of the mechanism of combustion is too vague to allow more than the a priori conclusion that decrease in droplet size should increase the rate of combustion and diminish the time for complete combustion. Correlation of the spray properties of injectors with their performance in the combustion chamber must be made the means of determining the order of magnitude of the influence of drop size on performance.

The combustion efficiency of a motor depends upon the degree of atomisation, the rate of combustion of the propellant, and the time spent by the propellant in the combustion chamber. The combustion efficiency of a particular injector/combustion chamber system may be measured by determining the ratio of the actual to the theoretical specific impulse; the time spent in the combustion chamber is not easy to calculate, but methods could be found of measuring its mean value. It is usually assumed to be proportional to the value of L^x the ratio of combustion chamber volume to throat area although for cylindrical chambers the length would seem to be a sufficient criterion. For a given injector and propellant system a minimum L^x can be found at which the efficiency begins to fall off. The injector should then be modified so as to vary the droplet size of distribution, while affecting the time spent by the propellant in the combustion chamber as little as possible. Until such a programme of

/research

* In Part I of this Report it is shown that the theoretical depth of field for a 20μ circle of confusion is 1.6 mm.

research is under way, measurements of the spray properties of particular injectors are of limited interest, and the following examples are quoted only to show the scope of the photographic technique.

Figure 4 shows sections of negatives of the spray produced by an injector designed for a 100 lb. Dithkite motor. The injector (drawing No.4012) is a single orifice swirl type having interchangeable swirl plugs, one in the form of helical screw and the other (drawing No.4018) having four tangential inlets and a central orifice. The former gives a hollow cone spray of angle 60° and the latter an unsymmetrical distribution illustrated in fig.7. The throughputs are similar and the results of a water test are plotted in litres of water per second against the square root of pressure head, (atmospheres)², in fig. 8. The photographs shown in fig.4 are taken with water as the sprayed liquid at injection pressures of 6, 9 and 15 atmospheres with each of the swirl plugs. They illustrate the relative inefficiency of the tangential plug used; since the differences in the two sprays were of high order, no attempt was made to examine the spray over the entire cross section. Several samples were taken at points which represented the major part of the liquid flow at a distance of about 20 cms. from the orifice, and the portions of the negative shown are roughly representative of the spray as a whole. Fig. 5 shows the drop size distribution of the spray sample given by the two types of insert as a function of injection pressure. The diameters above which lie a fraction 0.5 of the spray volume (termed the volume median diameter), are tabulated below:-

Type of insert	Water Injection Pressure in atmospheres		
	6	9	15
Helical	250 μ	225 μ	150 μ
Tangential with central hole	650 μ	570 μ	370 μ

The results are presented in the form of curves and the volume median diameter because the imprecision of the method does not allow the distribution to be fitted to a curve of the form $R = e^{-\frac{d}{d_0}}$ and characterised by the two constants d_0 and n .

The volume median diameters decrease with increasing injection pressure but those with the helical screw insert are consistently rather less than half those obtained with the slotted plug. Figures 9 and 10 illustrate the appearance of the spray on leaving the orifice. It would appear that the velocity losses in the swirl chamber of the injector when using the tangentially slotted plug are much greater than those with the helical screw. The relatively poor atomisation of the former must be in part due to the lower relative air-liquid velocity. The shape of the drop images indicates that even at 20 cm. from the orifice secondary break up of the drops is occurring.

In order to obtain an estimate of the effect of surface tension, photographs were also taken using kerosine as the sprayed liquid. The variation with pressure and injector type is similar to that of water, values of the volume median diameter at comparable values of $\Delta P/p$ being about 25% less than those with water.

The second example illustrates the methods of averaging the drop size distribution curves over the spray volume to get the distribution curve representative of the whole spray. The injector (drawing No.4007) had been designed for a 100 lb. motor operating on nitric acid and kerosine, the latter being injected from a central swirl nozzle and the

/nitric

nitric acid coming through an annular orifice concentric with the kerosine orifice. The inner kerosine spray has a cone angle of about 100° ; the distribution of liquid across a cross section of the spray is shown in figure (11). The patterning tray is divided into four quadrants numbered 1, 2, 3, 4 which are subdivided into annular zones lettered A, B, C, D and E starting from the periphery of the spray. The figures in each compartment represent the fraction of the spray falling in that compartment. The positions at which sample photographs were taken, correspond to the midpoint of each quarter zone. The set of negatives corresponding to each annular zone A, B, and C are assessed together; the same negative area being covered in each of the four positions denoted by the figures 1, 2, 3 and 4. The total area is such as to give a count of between 500 and 1000 droplets. Having obtained a distribution curve for each annulus they are averaged over the three zones A, B and C, the fraction of the spray falling in the central zones being small in the present instance.

Thus if v_j are the volume fractions in each zone and R_N is the fraction oversize at any droplet diameter

$$R = \frac{\sum_j v_j R_j}{\sum_j v_j} \quad (4)$$

The distribution curves for the A, B and C zones together with the mean curve are shown in figures (11) for the Kerosene spray at 6 atmospheres injection pressure. The values of the volume median diameter against injection pressure are tabulated below.

Injection pressure in atmospheres	6	9	15
Volume median diameter in	190	160	160

The outer annular orifice intended for the oxidant was tested with water. The cone angle was 110° and the spray formed a hollow cone of which the overall thickness was not more than 2 cms at a distance of 20 cms. from the orifice. No attempt was made to subdivide this in zones since the mean diameter of the droplets was such that the depth of the spray was covered by one focussing distance.

Injection Pressure in atmospheres	1	3	6	9	15
Volume median diameter in	600	530	500	530	480

The effect of increasing injection pressure in decreasing the median droplet size of the spray is rather smaller for this injector than any of the others examined. It is probably related to the larger cone angle of the spray.

Programme of Research

The examples given of spray droplet size determination show that a fair degree of accuracy can be obtained by direct photography. The time and labour involved increase with the degree of accuracy, and in order to determine the precision needed it is therefore necessary to investigate the effect of spray droplet size on the functioning of rocket motors.

The problem of designing a series of injectors for correlation with proofstand tests giving a wide variation in mean droplet size but with similar distribution patterns is not an easy one. The last

/point

point is of particular importance in bipropellant systems where the degree of mixing of the two components must in part determine the combustion efficiency. The effect of changes in droplet size will be clearer in monopropellant motors or those in which the components are premixed. The multi orifice injector seems to offer the best approach but if the individual orifices are to be made large enough to eliminate trouble due to blocking it is necessary to use motors of over 500 lbs thrust. In the meantime a nitric acid/kerosene injector for a 500 lb. motor is being designed to use interchangeable Todd orifice plates of which the number and size of orifice can be easily varied.

The photographic technique will also be used to study the process of atomisation under temperature and flow conditions similar to those in the combustion chamber and possibly to measure the rate of combustion of small droplets of monopropellants.

Acknowledgments

The author wishes to acknowledge the assistance of Miss Joan Quinn and Mr. P.W. Gray in the experimental work described in this report.

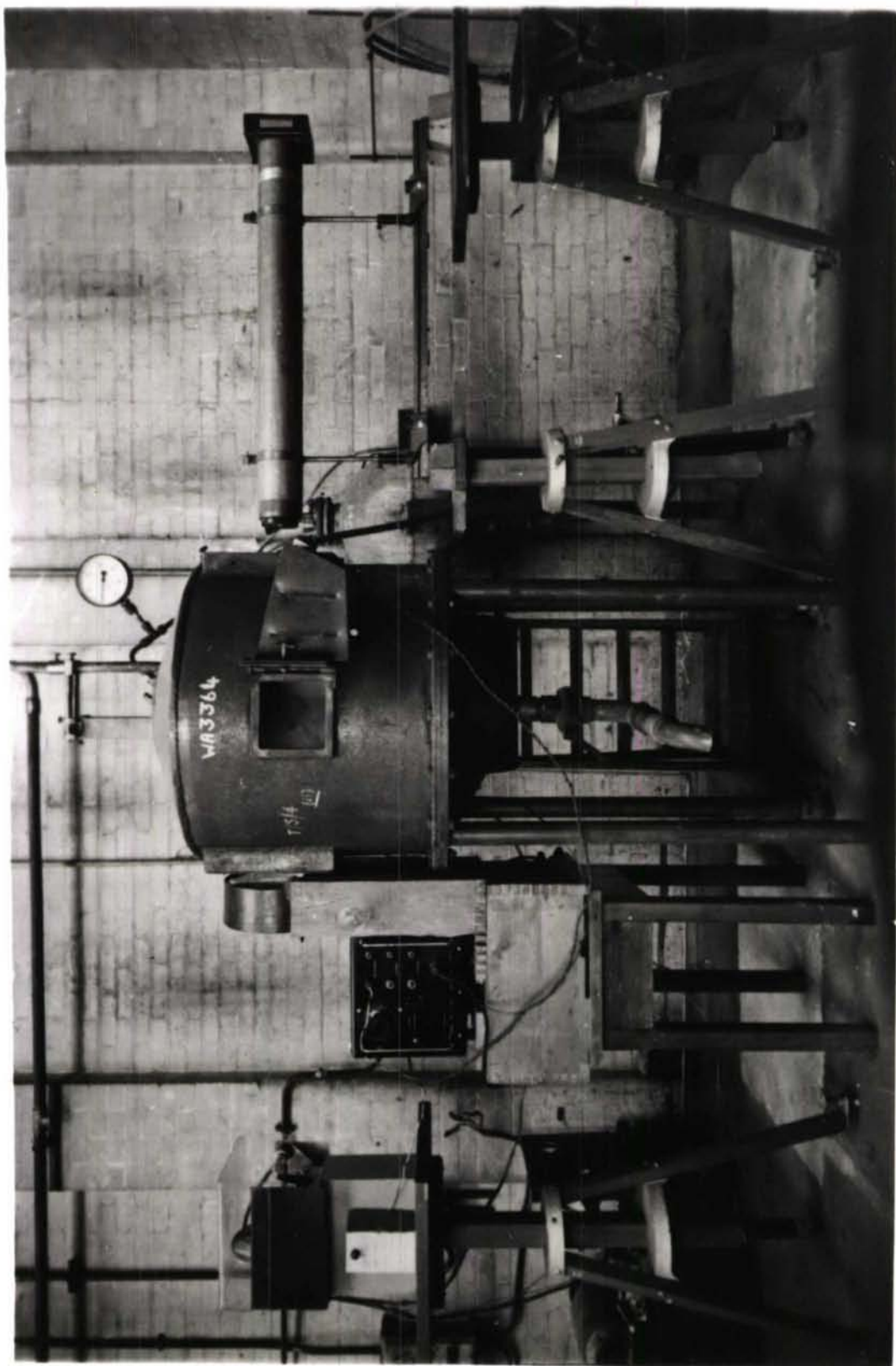


FIG. 1

TELEPHONE CALL REGISTERS

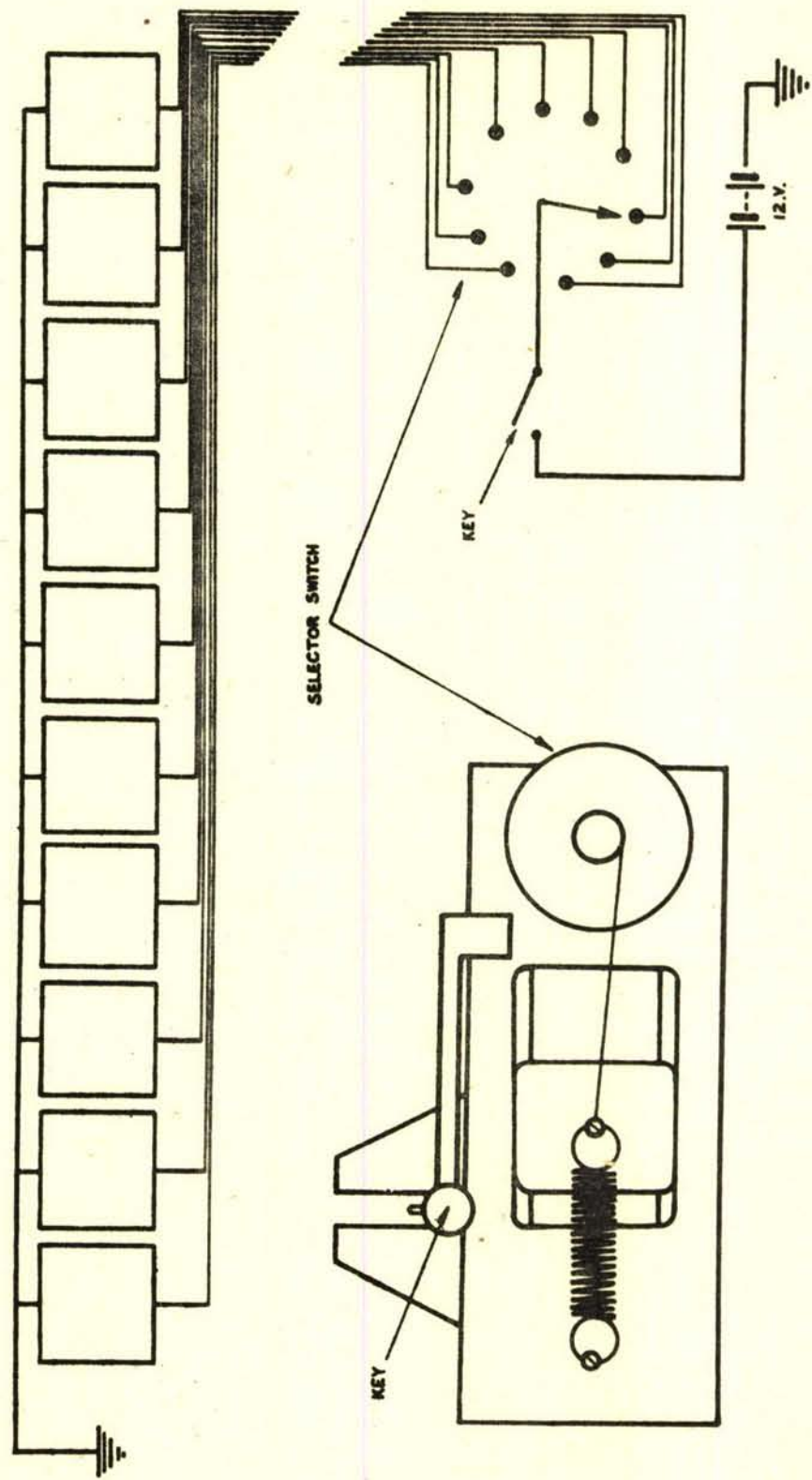


FIG 3

WATER INTO AIR AT 1 ATMOSPHERE

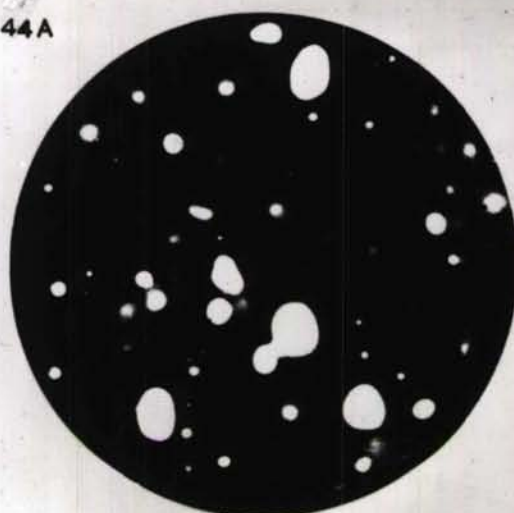
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INJECTION PRESSURE HEAD
IN ATMOSPHERES

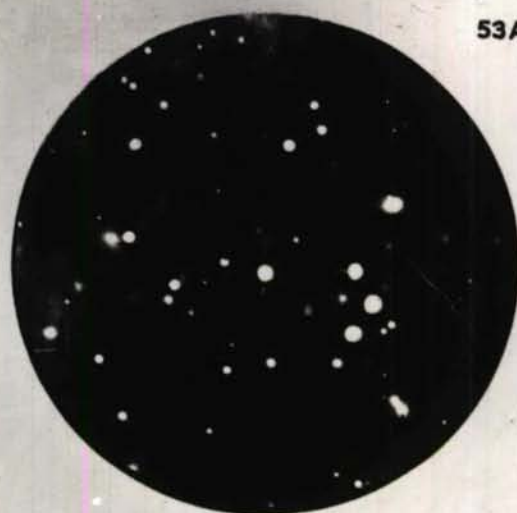
NEGATIVE N°

44 A

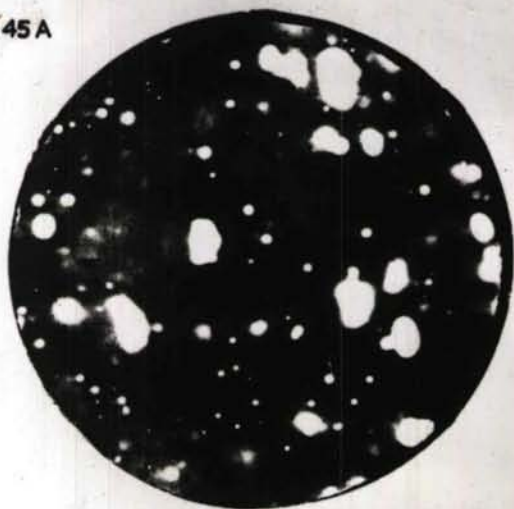


6

53 A

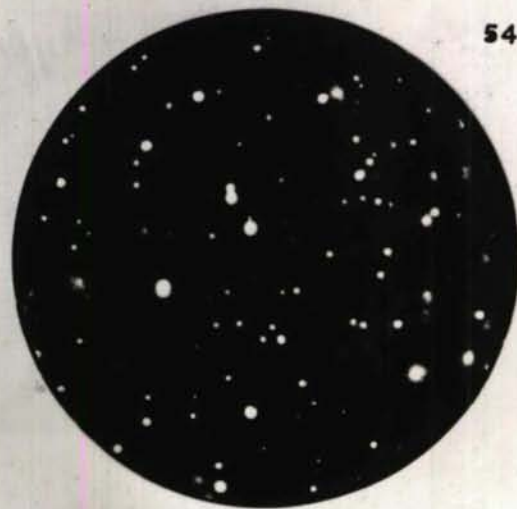


45 A



9

54 A



46 A



15

55 A

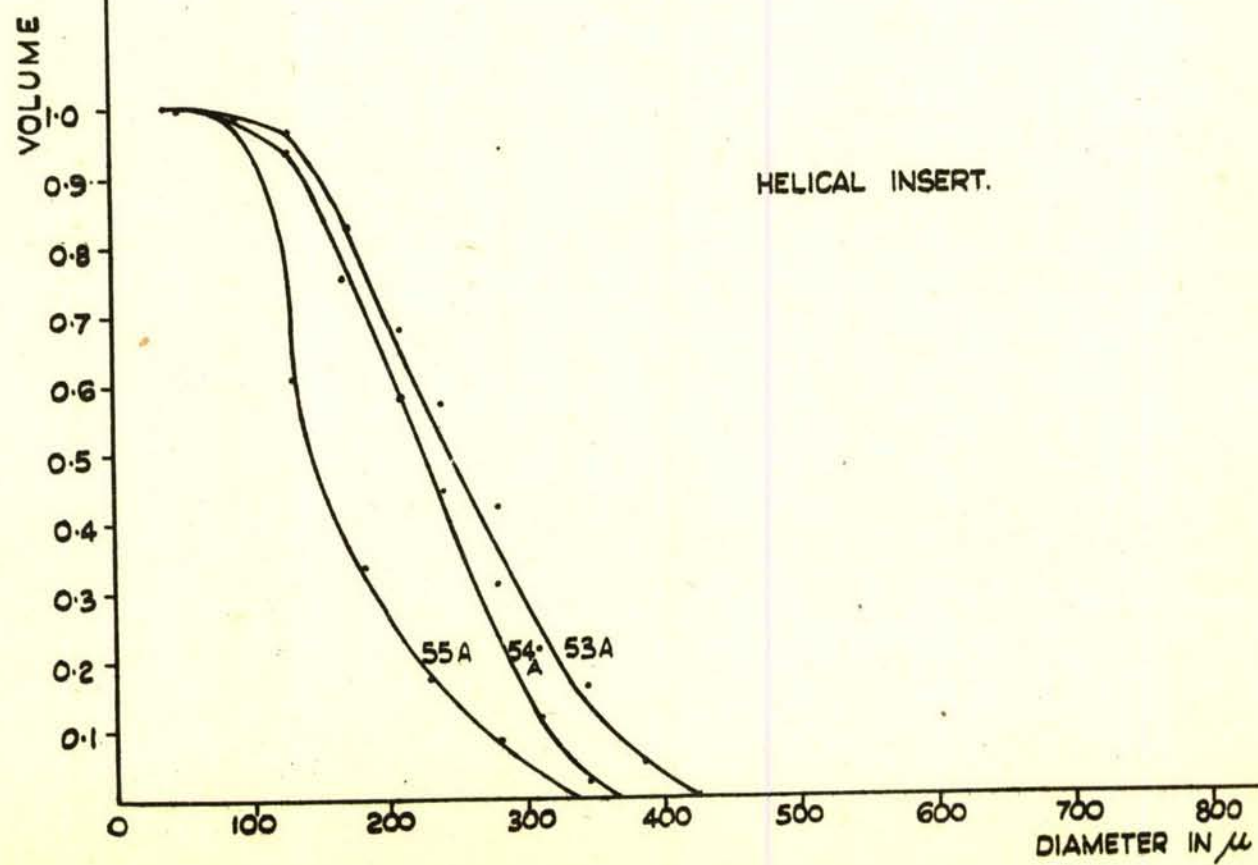
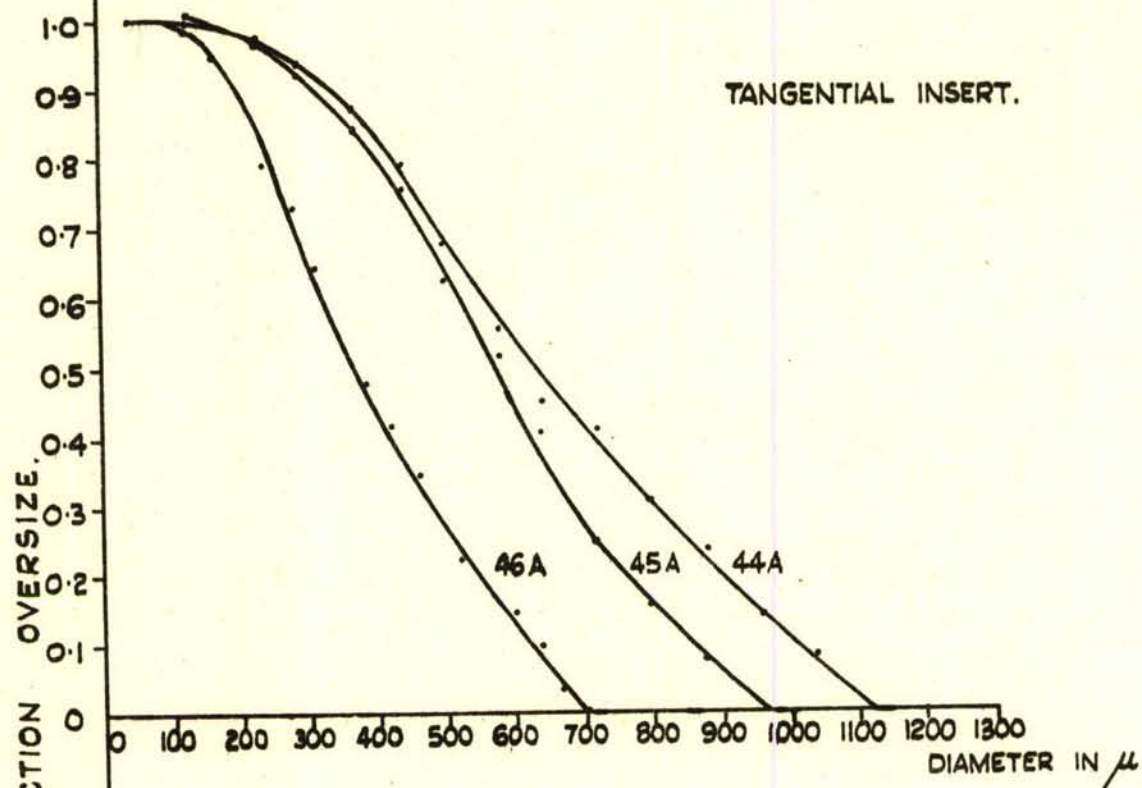


TANGENTIALLY SLOTTED PLUG
DRAWING N° 4014

HELICAL PLUG INSERT
DRAWING N° 4018

DITHEKITE INJECTOR.

FIG. 5.



DITHEKITE INJECTOR. FLOW CALIBRATION

FIG. 8.

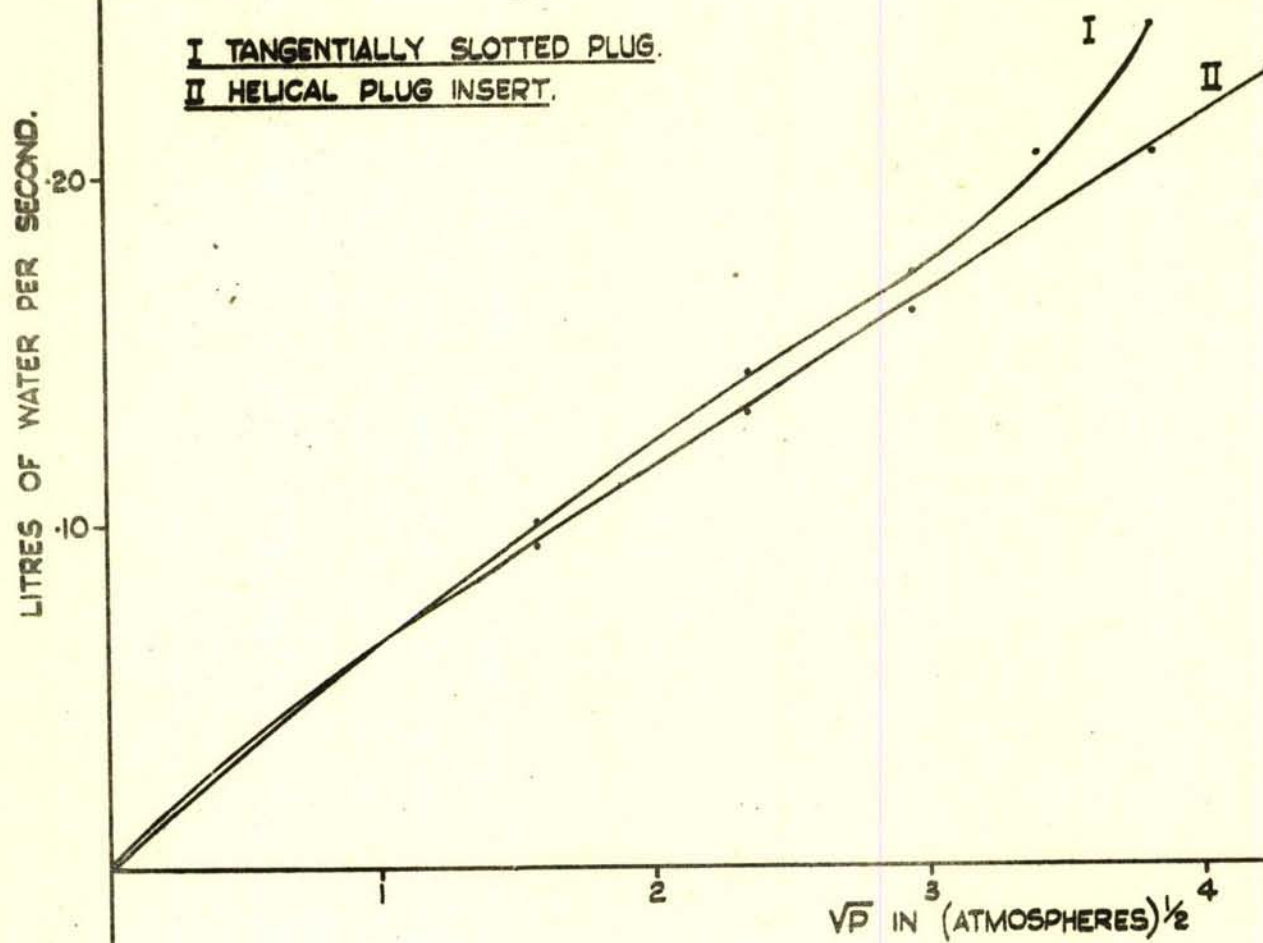


FIG. 6.

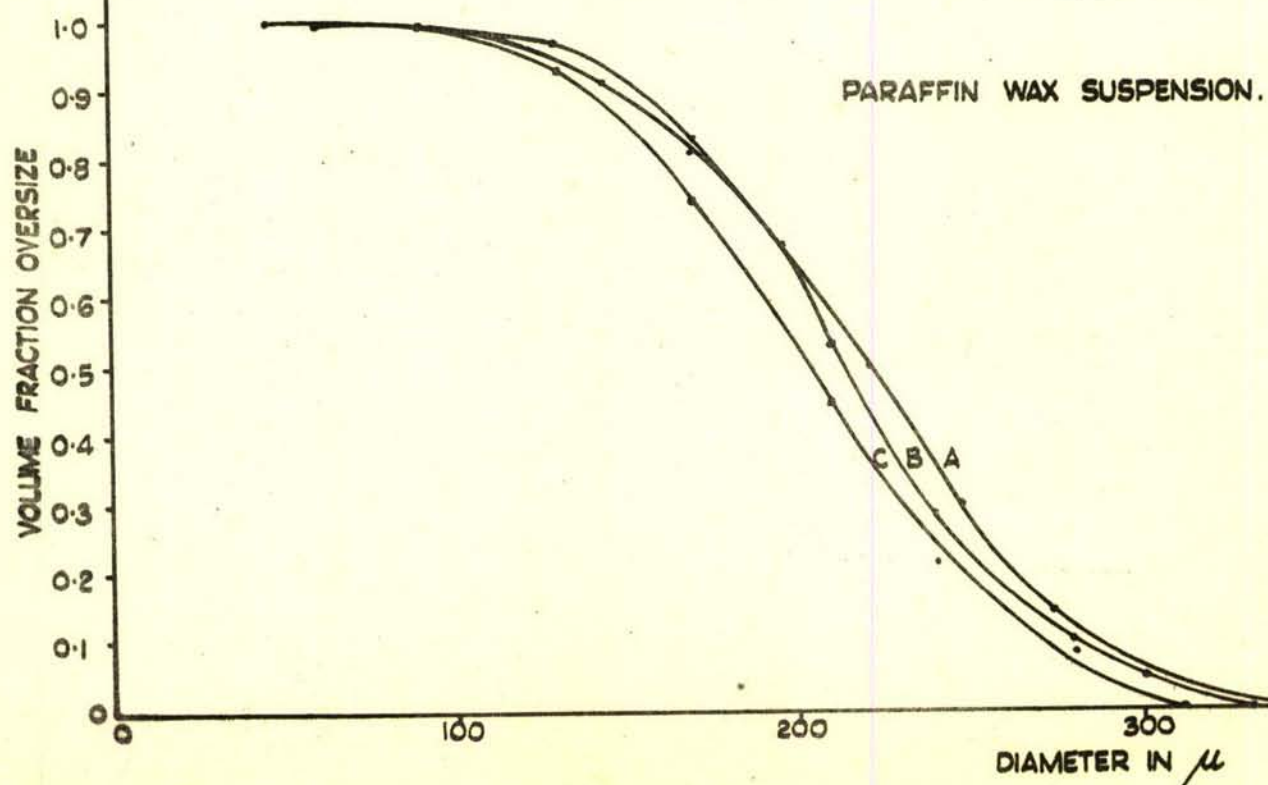


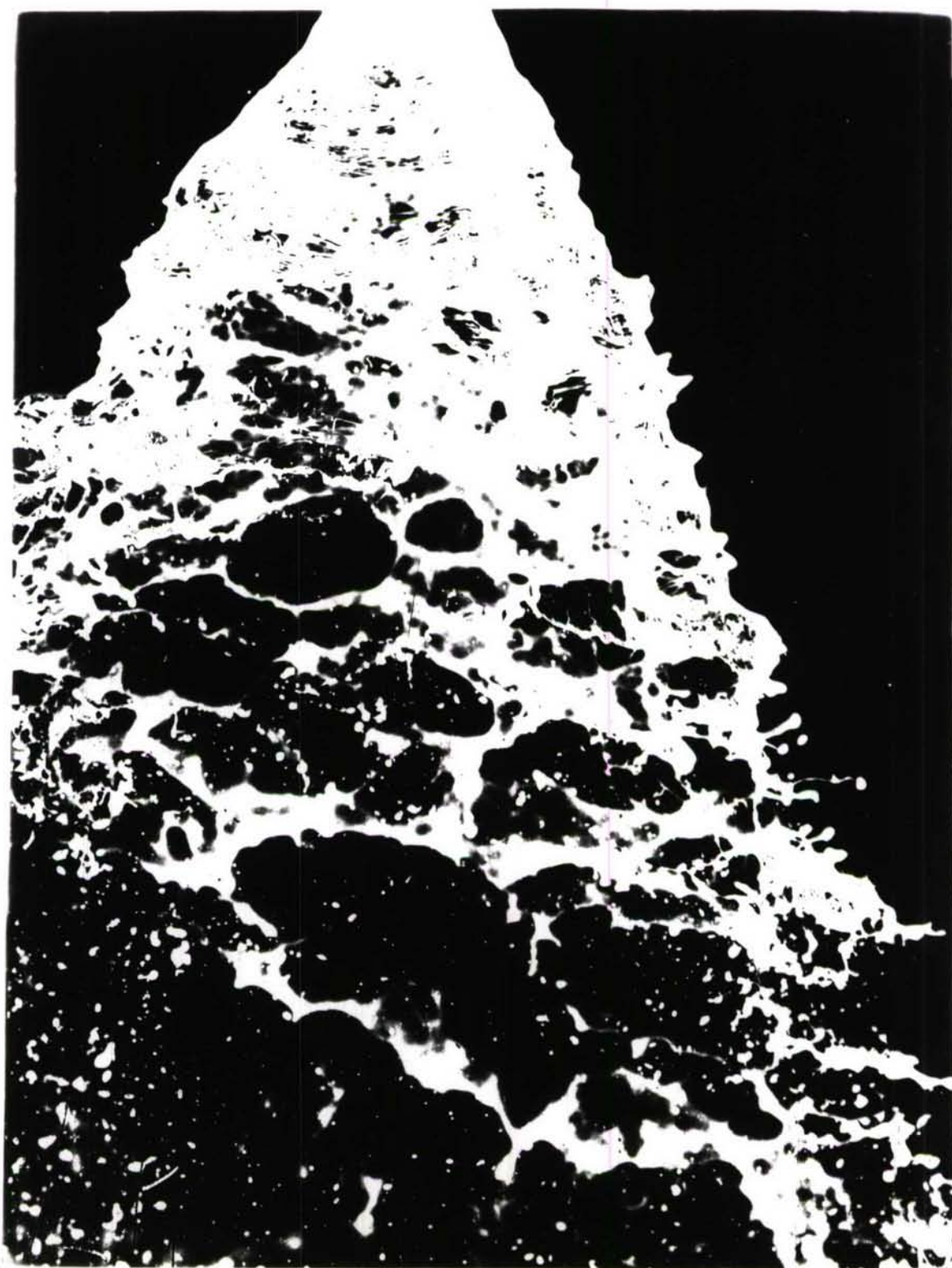


FIG. 7

FIG 9.

DITHEKITE INJECTOR WITH HELICAL PLUG
DRAWING N° 4014

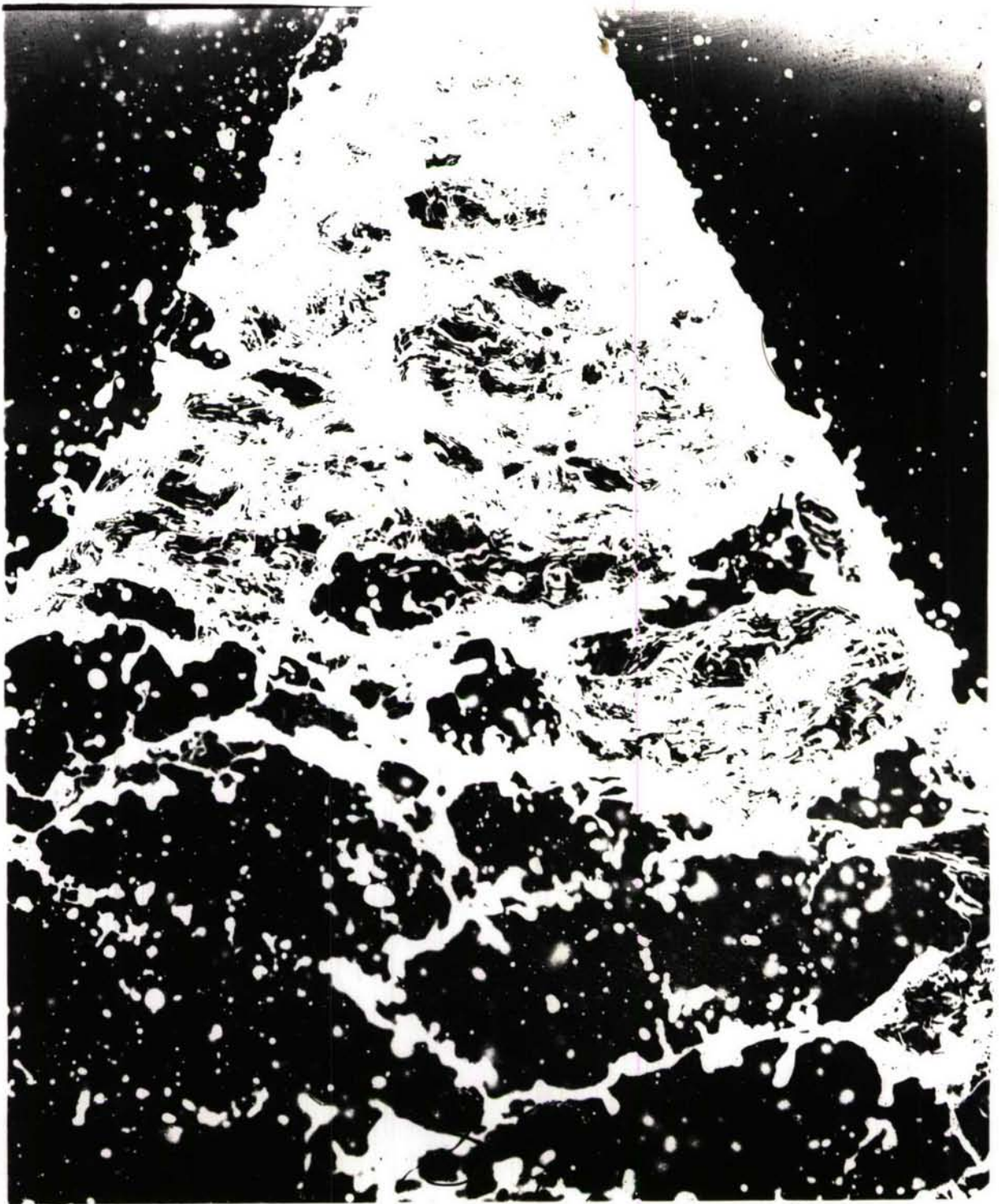
WATER INTO AIR AT 1 ATMOSPHERE
INJECTION PRESSURE 6 ATMOSPHERES
MAGNIFICATION X 4.2
NEGATIVE N° 47



UNCLASSIFIED

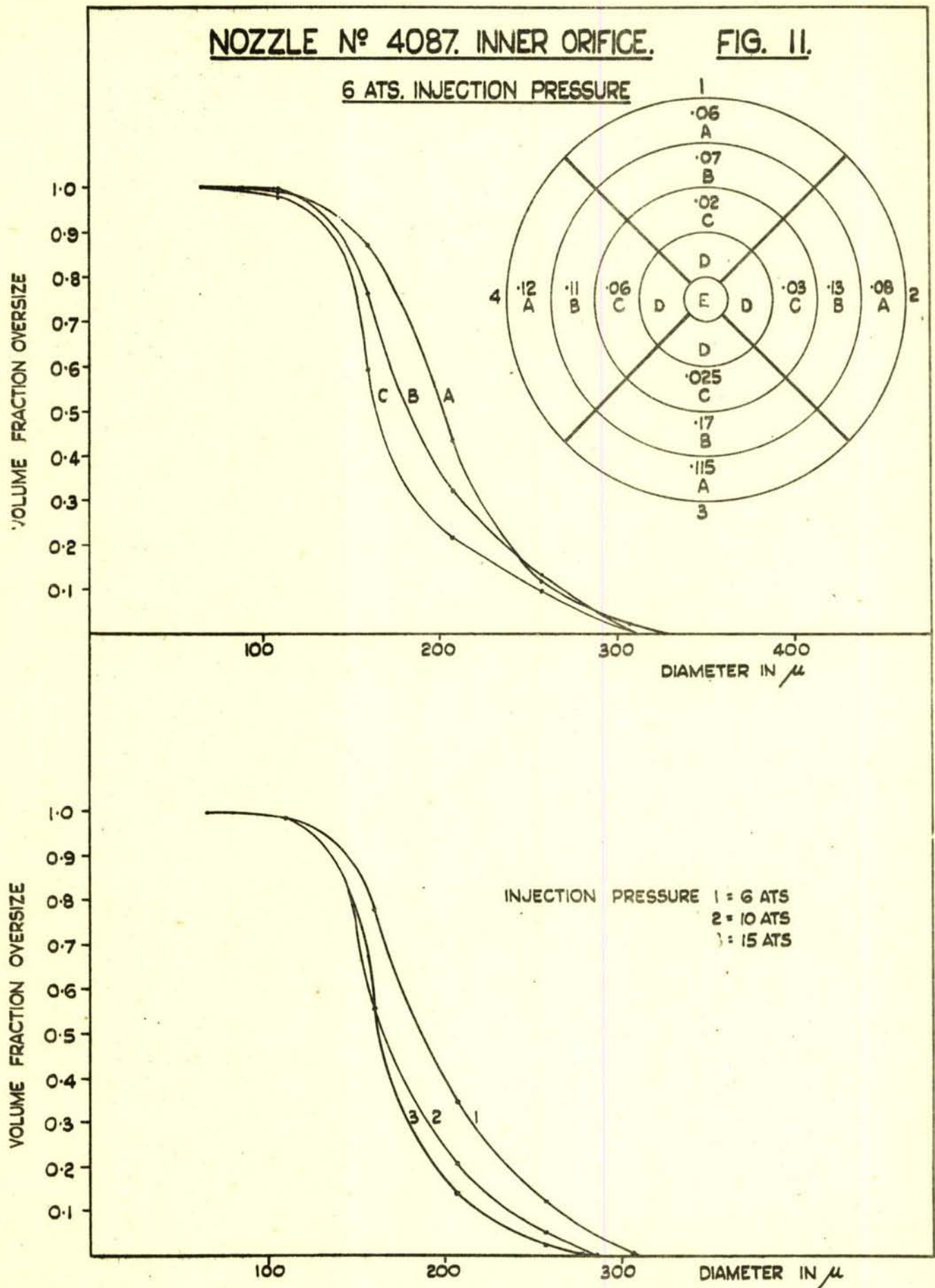
FIG 10.

DITHEKITE INJECTOR WITH TANGENTIALLY SLOTTED PLUG
DRAWING N° 4018
WATER INTO AIR AT 1 ATMOSPHERE
INJECTION PRESSURE 6 ATMOSPHERES
MAGNIFICATION X 4.2
NEGATIVE N° 38



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